Scaling of Electron Beam Switches

Peter Bletzinger
Air Force Wright Aeronautical Laboratories
Wright Patterson Air Force Base, Ohio

Abstract

Important design parameters of E-beam controlled discharges to be used as switches are the ratio of discharge current to E-beam current (current gain), the discharge current density and the discharge voltage. Measurements of these parameters as a function of E-beam current are presented and compared to theoretical predictions. These measurements also allow extrapolation to higher E-beam or discharge current densities. The influence of added attaching gases is considered also. Gases which have an attachment coefficient rapidly increasing with electric field have been tested. While the basic effect has been verified, the range of electric fields over which it occurs seems to be limited.

Introduction

At the 3rd pulse power conference, it was shown (1) that using a small current density (less than 1.5 mA/cm²) E-beam, discharge current densities more than 1000 times larger than the E-beam current density could be controlled with the E-beam. The discharge voltage with atmospheric pressure CH_4 or a mixture of 60 Torr of argon in 1 atmosphere of CH_4 was about 1Kv for these operating conditions. While these low current density, high gain conditions may be suitable for some applications, it was of interest to extend the operating parameters and obtain scaling laws for higher current density operation. This also would test theoretical predictions for E-beam switches (2). Another potential disadvantage of the low current density regime is the slow switching speed, especially for the"off" phase. For most gases considered, the current decay is recombination dominated; since the recombination coefficient is decreasing strongly with increasing electric field, its effect on switch-off speed will decrease during the increase of the voltage. As has been pointed out already in (1), the addition of small amounts of attaching gases can make the current decay attachment dominated and increase the switch-off speed in accordance with the amount of attacher added, but at the expense of current gain. The chemical stability of the attacher used (SF6) and the fact that due to its large attachment coefficient only a very small amount could be added, reduced its effect after only a few discharges. Recently a number of attaching gases were proposed which have the very desirable characteristic of an attachment coefficient which increase very strongly with increasing electric field (3). These and other attaching gases have been tested experimentally and compared with attachment coefficients measured by other methods.

Experiment

The E-beam used is the same described previously (1), except that the maximum beam current density was raised to 20 mA/cm² and the switch-off time was reduced to less than 10^{-6} sec. The beam aperture was 5 X 15 cm and the energy 175KeV. The discharge section and flow loop also remained unchanged; the electrode distance could be varied very accurately with a stepping motor driven micrometer from 0 to more than 3 cm. The discharge circuit again consisted of a 1 microfared storage capacitor and a 4 Ohm load resistor, if used. Data was collected with a waveform analyzer.

Voltage and Current Scaling

Operating parameters for electron beam controlled switches have been computed, based on gas transport calculations (2). We want to compare these calculations with experimental results and also extend the scaling to include attachment. The parameters of interests are the switch current gain (discharge current vs. electron beam current) and the discharge or switch voltage for the "on" condition.

These parameters of course also depend on gas pressure and electrode distance, which are mainly determined by the required hold-off voltage. Another parameter, which may set a lower limit on the electron beam current is the required rise time of the "on" phase of the switch. In the gases considered and with the operating conditions selected, the loss processes are dominated by recombination, then the discharge electron density is governed by the well known relation

$$n_e = \sqrt{\frac{S}{\alpha}}$$

where S is the source strength (number of electrons generated per cm³ per sec) and α is the recombination coefficient (cm³ sec^{-1}).

If an attaching gas is added, this equation is modified to

$$n_e = \sqrt{\frac{S}{\alpha} + \left(\frac{\nu_a}{2\alpha}\right)^2} - \frac{\nu_a}{2\alpha}$$

where ν_a is the attachment frequency (sec^{-1}), and, if attachment dominated, n_e becomes a linear function of the source strength:

$$n_e = \frac{S}{\nu_a}$$

For the parameter range of interest, these relations are illustrated in fig. 1. At very large source strength, the electron density for a gas mixture with attacher again becomes recombination dominated. In order to check these relations experimentally, the discharge has to be operated at constant voltage such that the variation of the electron drift velocity with electric field is eliminated and the discharge current is proportional to n_e. In fig. 2 the data for an E-beam current density range of 0.7 - 23 mA/cm² (before the foil) for a discharge voltage of 2kV is shown; a fitted curve, representing the square root relationship of n_e and S, has been added.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JUN 1983**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **Scaling of Electron Beam Switches**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Air Force Wright Aeronautical Laboratories Wright Patterson Air Force Base, Ohio**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License

14. ABSTRACT
Important design parameters of E-beam controlled discharges to be used as switches are the ratio of discharge current to E-beam current (current gain), the discharge current density and the discharge voltage. Measurements of these parameters as a function of E-beam current are presented and compared to theoretical predictions. These measurements also allow extrapolation to higher E-beam or discharge current densities. The influence of added attaching gases is considered also. Gases which have an attachment coefficient rapidly increasing with electric field have been tested. While the basic effect has been verified, the range of electric fields over which it occurs seems to be limited.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Note that at very low E-beam current densities cathode sheath effects tend to lower the discharge current. Also shown is the data for an added attaching gas (18 Torr of CF_4 added to CH_4, total pressure 1 atmosphere). For very low E-beam current densities again cathode sheath effects mask the relationship, but for the range of 2-6 mA/cm² (before the foil) the relation of discharge current to E-Beam current is almost linear and for higher current densities again follows the recombination dominated curve. Simply dividing by the E-beam current (adjusted for 45% foil transmission), we obtain the data for current gain. Extrapolating the experimental data, at a discharge current density of 10A/cm², a postfoil E-beam current density of .06A/cm² is required (current gain 167).

Another important scaling parameter is the voltage drop across the switch as a function of switch current density. Again considering a recombination dominated discharge, we have to include the dependence of both recombination coefficient and electron drift velocity on the electric field

$$j_d = n_e \cdot e \cdot v_d = \sqrt{\frac{S}{\alpha(E/N)}} \cdot e \cdot v_d(E/N)$$

where jd = discharge current density
v_d = electron drift velocity
E/N = reduced electric field (N: neutral density)

Using E or the discharge voltage as the independentvariable, the source term S and with it the E-beam current density can be computed with the discharge current as parameter and using the transport data calculated by L. Kline (2). From previous experiments, the recombination coefficient was found to be ten times the original data (1) and this is included in this computation. In fig. 3 the computed data is compared with experimental data for a discharge current density of 0.33 A/cm². The foil transmission of the E-beam was assumed to be 45%, a value which is probably somewhat high for the E-beam used. The experimental discharge voltage is almost a factor of three larger than the theoretical voltage. To assess the cathode fall voltage, not considered in this simple theory, each measurement was repeated with different electrode distances keeping the discharge current constant. Extrapolating the measured discharge voltages to zero distance, the cathode fall voltage for each point was obtained. As shown in fig. 3, when these cathode fall voltage values are subtracted from the measured discharges voltages, a good match to the theoretical curve is obtained. Unfortunately, the cathode fall voltage, being a function of E-beam current, discharge current, gas type and pressure, secondary emission coefficient of the cathode material and other parameters, is rather difficult to calculate (4). Experimental data for the discharge voltage (minus cathode fall voltage) for the gas mixture with attacher show an expected increase of the discharge voltage. Fig. 4 shows the cathode fall voltage as a function of E-beam current density for discharge current densities of 0.34 and 0.67 A/cm². The influence of discharge current is small, however even at large E-beam currents, the cathode fall voltage decreases very slowly and for atmospheric pressures is considerably larger than the voltage across 2.2 cm of discharge. As already suggested in (5) and (4), a cathode materials with better electron emission characteristics can lower this voltage. The addition of an attaching gas does not seem to increase the cathode fall voltage very much, the increase in discharge voltage is mostly due to an increase of the voltage drop across the main volume of the discharge.

Effect of attaching gases on decay time

When the E-beam ionized discharge is used as a switch, on switching off, the voltage across the discharge will increase by one or two orders of magnitude in most applications considered. For gases such as nitrogen or methane, the recombination dominated decay will then be very long, since the recombination coefficient decreases rapidly with increasing electric field. Several attaching gases, including some which were suggested for their rapidly increasing attachment rate with electric field (3), were tested. Fig. 5 shows results for nitrogen at a discharge voltage of 2KV and an E-beam current density of 5mA/cm² (before the foil). In methane, fig.6, (same E-beam current density and discharge voltage) the current decay is inherently faster, due to the higher recombination coefficient. Note that with a loss of only about 30% in discharge current, the added attaching gases reduce the decay time (90% to 10% amplitude) to less than 50 % of that of pure methane, but even more effectively remove the long tail of the recombination dominated decay. Fig. 7 shows a comparison of the discharge current decay at two different discharge voltage for pure methane and for methane with C_2F_6 added. As expected, the methane decay is slower at the higher voltage, however with the attaching gas added, the trend is reversed. In the experiments however, this increase in attachment rate was found only over a limited range of voltages, at higher discharge voltage the attachment rate would decrease. The reasons for this at present are not clear; if the attaching gas dissociates, it could form F_2, which has a much higher attachment coefficient but which decreases with increasing electric field.

Conclusions

It was shown that the simple model for the E-beam ionized discharge describes the behavior of the discharge current adequately. However, available transport data will allow calculation of the discharge voltage only when experimental values for the cathode fall voltage are included. The cathode fall voltage is not negligible even at high E-beam currents but could possibly be lowered with special treatment of the cathode material. The E-beam controlled discharge then can be scaled over a wide range of discharge current densities. Current decay times can be lowered by adding attaching gases, but the increase of attachment rate with increasing electric field has been observed over a limited range only.

References:

(1) P. Bletzinger "Electron Beam Switching Experiments in the high current gain regime", 3rd IEEE Intl. Pulsed Power Conference, Albuquerque, 1981

(2) L.E. Kline " Performance predictions for electron-beam controlled on/off switches", IEEE Trans Plasma Science PS-10,224, Dec 82 and J.W. Dzimianski & L.E. Kline "High voltage switch using externally ionized plasmas", AFWAL-TR-80-2041, 1980
(3) L.G. Christophorou, S.R. Hunter, J.G. Carter and R.A. Mathis "Gases for possible use in diffuse-discharge switches, "Appl. Phys. Lett. 41, 147 (1982)
(4) M.R. Hallada, P. Bletzinger & W.F. Bailey "Application of electron-beam ionized discharges to switches - a comparison of experiment with theory", IEEE Trans. Plasma Science PS-10, 218, Dec 82
(5) E.P. Velikhov et. al. "The nonself-sustaining gas discharge for exciting continous-wave gas laser "Sov. Phys. - Usp., 20, 586 (1977)

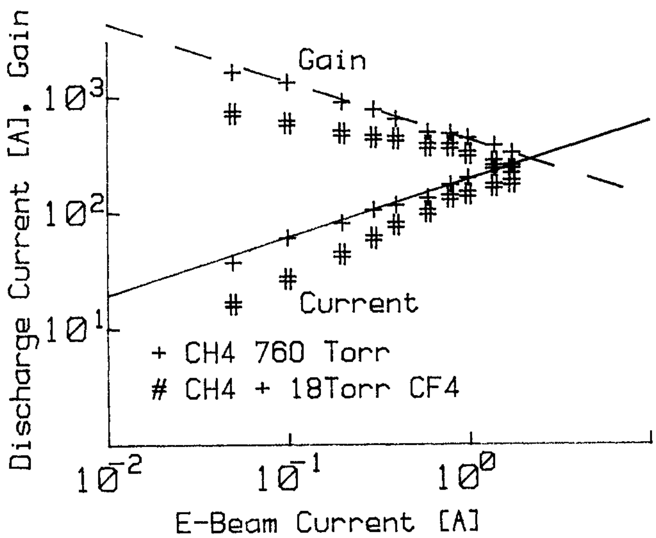

FIG 2. DISCHARGE CURRENT AND CURRENT GAIN AS FUNCTION OF E-BEAM CURRENT, DISCHARGE VOLTAGE 2 kV, DISCHARGE AREA 75 cm^2. E-BEAM CURRENT MEASURED BEFORE THE FOIL, TRANSMISSION FOR CURRENT GAIN ASSUMED TO BE 45%.

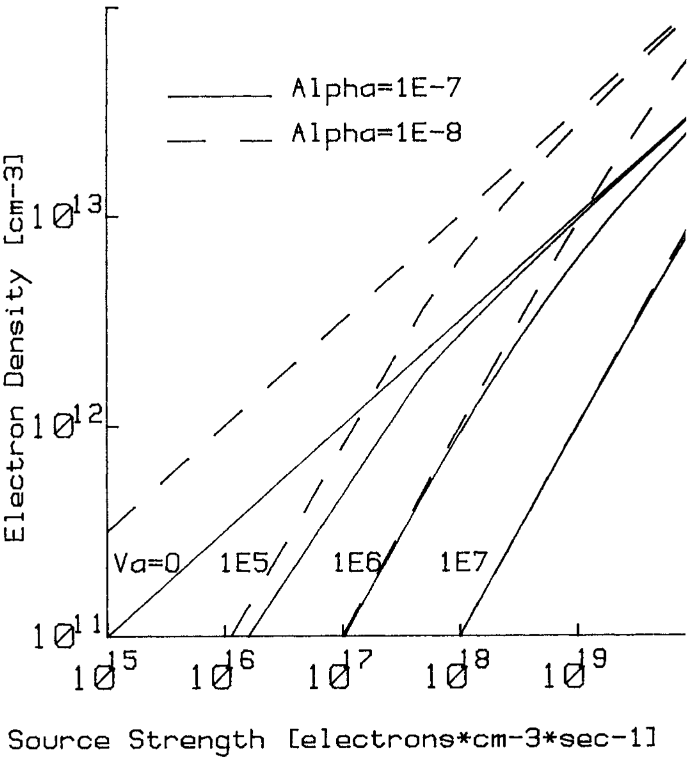

FIG 1. ELECTRON DENSITY AS FUNCTION OF E-BEAM SOURCE STRENGTH, RECOMBINATION COEFFICIENT α AND ATTACHMENT FREQUENCY ν_a PARAMETERS

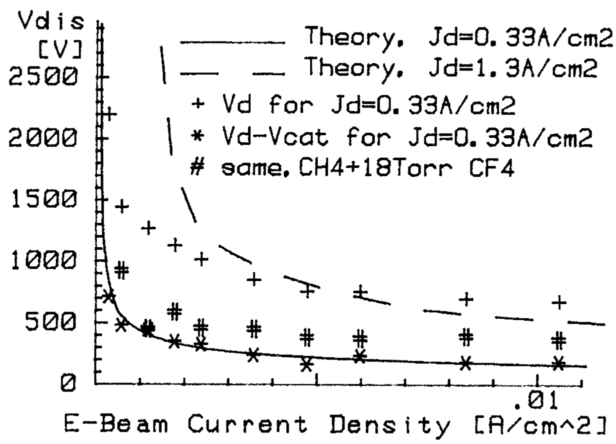

FIG 3. DISCHARGE VOLTAGE AT AN ELECTRODE SPACING OF 2.2 cm AS FUNCTION OF E-BEAM CURRENT DENSITY (AFTER FOIL)

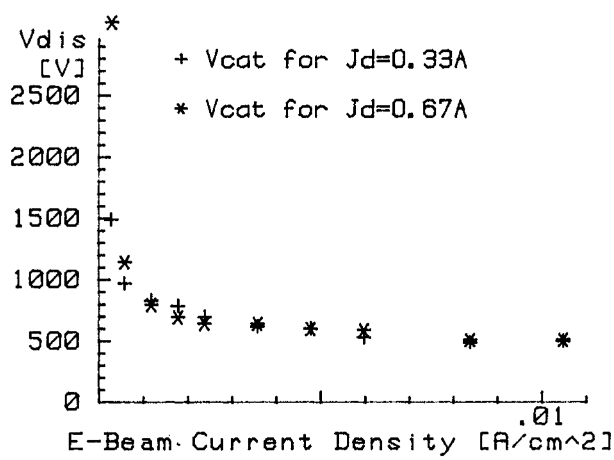

FIG 4. CATHODE FALL VOLTAGE AS FUNCTION OF E-BEAM CURRENT DENSITY (AFTER FOIL).

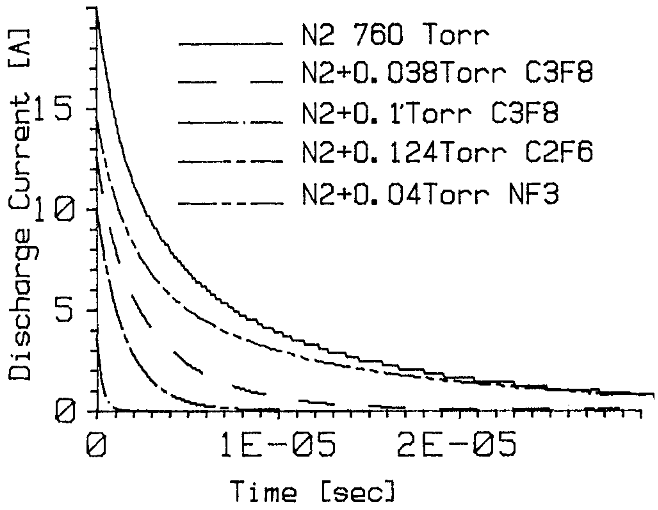

FIG 5. CURRENT DECAYS FOR NITROGEN AND NITROGEN WITH ADDED ATTACHING GASES.

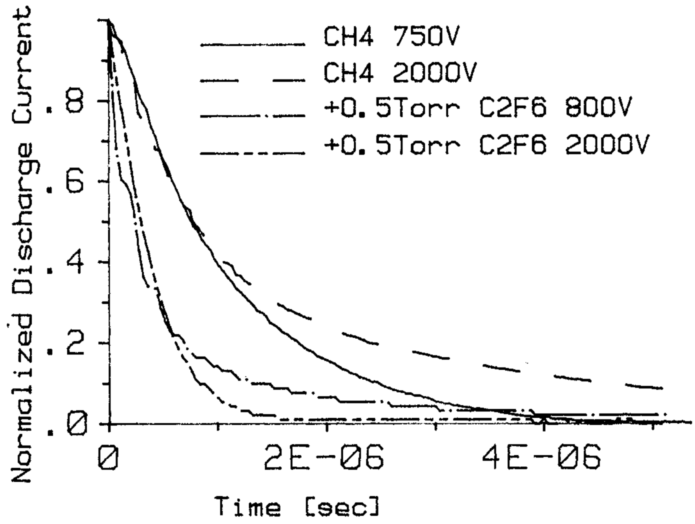

FIG 7. CURRENT DECAYS (NORMALIZED AMPLITUDES) FOR METHANE AND METHANE WITH AN ATTACHING GAS, DISCHARGE VOLTAGE PARAMETER (ELECTRODE DISTANCE 2.2 cm).

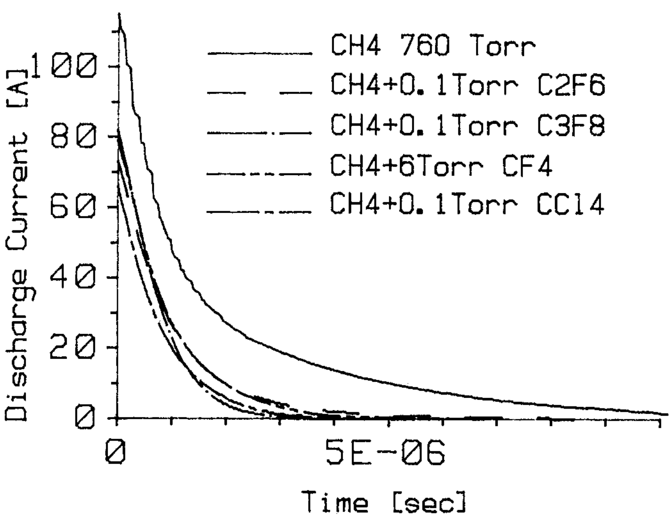

FIG 6. CURRENT DECAYS FOR METHANE AND METHANE WITH ADDED ATTACHING GASES.